

Inundation Dynamics in Braided Floodplains: Tagliamento River, Northeast Italy

Dimitry van der Nat,^{1*} Andreas P. Schmidt,¹ Klement Tockner,¹
Peter J. Edwards,² and J. V. Ward¹

¹Department of Limnology, Eidgenössische Anstalt für Wasserversorgung Abwasserreinigung und Gewässerchutz, Überlandstrasse 133, 8600 Dübendorf, Switzerland; and ²Geobotanical Institute, Eidgenössische Technische Hochschule, 8044 Zürich, Switzerland

ABSTRACT

The relationships among water level, inundated area, and shoreline dynamics were investigated in a bar-braided and an island-braided floodplain of the Tagliamento River in northeast Italy. Ground-based surveys with a differential global positioning system (aGPS) unit were used to delineate all aquatic-terrestrial interfaces (shorelines) in the active floodplain at different water levels. Despite complex inundation patterns, a highly significant ($P < 0.00001$) linear relationship between water level and arcsine square root of inundated area was found in both reaches ($y = 0.49x + 0.07$). A highly significant ($P < 0.00009$) second-order polynomial relationship occurred between water level and shoreline length ($y = 87.83 - 65.85x^2 + 169.83x$). Using these relationships as simple predictive models, we converted several years of water-level data into predictions for degree of inundation and shoreline length. The plot of the simulated degree of inundation strongly resembled the actual hydrograph. Complete inundation of the active floodplains occurred one or two times per year; however,

the degree of inundation at lower water levels was highly dynamic during most of the year. Simulated shoreline length averaged 171 m ha^{-1} (13.6 km km^{-1}), with a maximum of 197 m ha^{-1} (15.6 km km^{-1}) occurring during periods with intermediate water levels. The corresponding values determined with GPS were somewhat higher, with an average value of 181 m ha^{-1} (14.4 km km^{-1}) and a maximum of 214 m ha^{-1} (16.3 km km^{-1}). During major flood events, actual shoreline length decreased to 28 m ha^{-1} (2.1 km km^{-1}). Braiding index and upstream surface hydrologic connectivity were positively related to water level, whereas total area of isolated water bodies was negatively related to water level. The number of nodes remained high most of the time during the 2-year study period.

Key words: floodplains; inundation; shoreline length; water level; predictive model; connectivity; flood pulse; flow pulse; ground-based survey; Tagliamento River.

INTRODUCTION

Floodplains are complex physical features bordering rivers in braided, meandering, or anastomosing reaches. They are highly dynamic in the natural

state, because floods rework their morphology at various spatial scales (Hughes and Rood 2001; Ward and others 2002b). Hydrology is the primary driving force for morphological and ecological processes in floodplains (Junk and others 1989; Sparks and others 1990; Bayley 1991; Spink and others 1998; Tockner and others 2000b).

Many of the early concepts describing river ecosystems, such as the river continuum concept (RCC) (Vannote and others 1980), the nutrient spi-

Received 13 July 2001; Accepted 19 February 2002.

Present address for A.P.S.: Laboratory of Hydraulics, Hydrology and Glaciology, ETH, 8092 Zürich, Switzerland

*Corresponding author; e-mail: dimitry.vandemat@eawag.ch

raling concept (Newbold and others 1982), and the serial discontinuity concept (Ward and Stanford 1983), focused on longitudinal patterns and processes. The flood pulse concept (FPC) (Junk and others 1989) explicitly incorporates lateral interactions between the channel and the floodplain and suggests that the flood pulse is the most important physical variable for biological processes in tropical (Junk and others 1989; Bayley 1991) and temperate rivers (Tockner and others 2000b). The focus given to the lateral dimension by the FPC stimulated many studies that examined the ecological implications of flooding in stream and river ecosystems (for example, Sparks and others 1990; Bayley 1991; Spink and others 1998). Because of this increased awareness of river–floodplain interactions, the existing theories were amended to incorporate the lateral dimensions of river ecosystems (Ward and Stanford 1995; Fisher and others 1998).

Overbank flooding (flood pulses) may occur seasonally or unpredictably (Poff and Ward 1989). In addition, rivers may experience many smaller water-level fluctuations (“flow pulses” *sensu* Tockner and others 2000b) that occur well below bank-full discharge. Although they are not responsible for the main morphological restructuring of the ecosystem, these flow pulses may be important for creating and maintaining habitat heterogeneity and ecosystem processes (for example, see Benke 2001). Both aquatic and terrestrial areas in the floodplain experience frequent cycles of expansion and contraction because of small water-level fluctuations (de Vries 1995; Stanley and others 1997; Tockner and others 2000b). Contraction of aquatic habitats, for example, fragments populations, reduces habitat availability, and alters ecosystem processes such as primary production and nutrient cycling (Stanley and others 1997).

Expansion and contraction cycles control the availability of aquatic–terrestrial interfaces (shorelines). Shorelines are important habitats for a large spectrum of organisms, such as fish (Wintersberger 1996; Schiemer and others 2001), birds (Décamps and others 1987; Reich 1994), and terrestrial invertebrates (Bonn and others 2002). In larger rivers, shoreline habitats may serve as important flood refugia (Rempel and others 1999). Additionally, they control the transfer of matter between aquatic and terrestrial zones (for example, Naiman and Décamps 1997; Bardgett and others 2001; Ward and Wiens 2001). With increased channelization and regulation of rivers across the world (Petts and others 1989), shoreline habitat is becoming increasingly rare (Pinay and others 1990; Ward and others 2002a). It is important to investigate the relation-

ship between discharge and available shoreline habitat in the remaining free-flowing rivers to gain a better understanding of the functioning of river systems in their natural state. This insight, in turn, is of importance for increasing the chances of success of river restoration projects (Benke and others 2000). Cycles of expansion and contraction also determine the availability of several distinct aquatic habitats, such as backwaters, alluvial channels, and isolated pools. Increasing human pressure requires quantitative methods to predict how a river’s form changes when discharge is altered.

Remote sensing studies have focused on the hydromorphological dynamics of floodplains (for example, Lesack and Melack 1995; Mertes 1997). Aerial photography has been used to analyze long-term changes in channel configuration of streams (Gilvear and others 1995) and braided rivers (Warburton and others 1993). On shorter time scales, aerial photographs have been used to analyze the relationship between discharge and channel change in a braided river (Mosley 1982). Mosley (1982) showed that increased discharge increased the availability of deep-water habitat without influencing the availability of shallow-water habitat. Using aerial photography, Benke and others (2000) established a linear relationship between discharge and the arcsine of inundated floodplain area for the subtropical Ogeechee River in the southeastern United States. Passive microwave observations have been used to establish a relationship between discharge and degree of floodplain inundation in tropical wetlands (Hamilton and others 1996) and tropical rivers (Sippel and others 1998). Global positioning systems (GPS) have also been used to acquire spatial data from floodplains. For instance, repeated transect measurements were used to develop a digital elevation model (DEM), which was used to monitor channel change in a braided river in Scotland (Brasington and others 2000).

We applied differential GPS to gather spatial data from two braided floodplains at various river stages. GPS allowed us to acquire data rapidly at any water level, independent of airplanes or satellites. The river system that we investigated was distinctly different from the other systems studied so far because it represents the last large free-flowing Alpine river in Europe (Müller 1995; Ward and others 1999a). The goal of this study was to quantify the relationships among water level, inundated area, shoreline length, and system complexity in a bar-braided and an island-braided floodplain. Based on the relationship, a predictive model was generated to calculate the availability of floodplain habitats.

Study Site

The Tagliamento River is a seventh-order gravel-bed river located in northeast Italy. It has a catchment area of 2580 km² and a total length of 172 km. About 70% of its catchment area is located in the southern limestone dolomite Alps. Average elevation of the catchment is 1159 m a.s.l., with a maximum of 2781 m a.s.l. (Ward and others 1999a; Arscott and others 2000). Through a sequence of constrained, braided, and meandering reaches, it flows from the Alps to the Adriatic Sea. The river has many vegetated islands, which cover approximately 9% of the entire active floodplain (Ward and others 1999a). The active floodplain consists of three major landscape elements: water, bare alluvial sediments, and vegetated islands. Along the Tagliamento, active floodplain width is up to 1.5 km. The active floodplain is fringed by continuous riparian woodland (Ward and others 1999a; Gurnell and others 2000a).

Although the river has been subject to water abstraction and channelization (lowermost 25 km), it remains remarkably free of intensive management. Consequently, the Tagliamento still has an essentially pristine morphological character and a natural flood regime (Müller 1995; Ward and others 1999a). The hydrology is characterized by a pluvio-nival regime with frequent flash floods and flow pulses. Flood pulses generally occur in spring and autumn (Figure 1B) and have an extremely low degree of predictability (Campolo and others 1999). The average discharge at the location where the river leaves the Alps is approximately 90 m³ s⁻¹, and the 2-, 5-, and 10-year floods are estimated to be 1100, 1600, and 2150 m³ s⁻¹, respectively (Gurnell and others 2000a). For a more detailed description of the catchment characteristics and hydrodynamics, see Ward and others (1999a) and Gurnell and others (2000a).

This study was carried out in two morphologically distinct reaches, hereafter referred to as the "bar-braided reach" and the "island-braided reach" (reaches III and IV from Arscott and others 2000). The location of both reaches within the Tagliamento catchment is shown in Figure 1A. The bar-braided reach was located downstream of river kilometer 74. Under base-flow conditions, large areas of exposed sediments and multiple channels (Table 1) dominated this reach. Its active floodplain area was 103 ha, reach length was 1.4 km, and floodplain width was up to 1.0 km. The island-braided reach was located downstream of

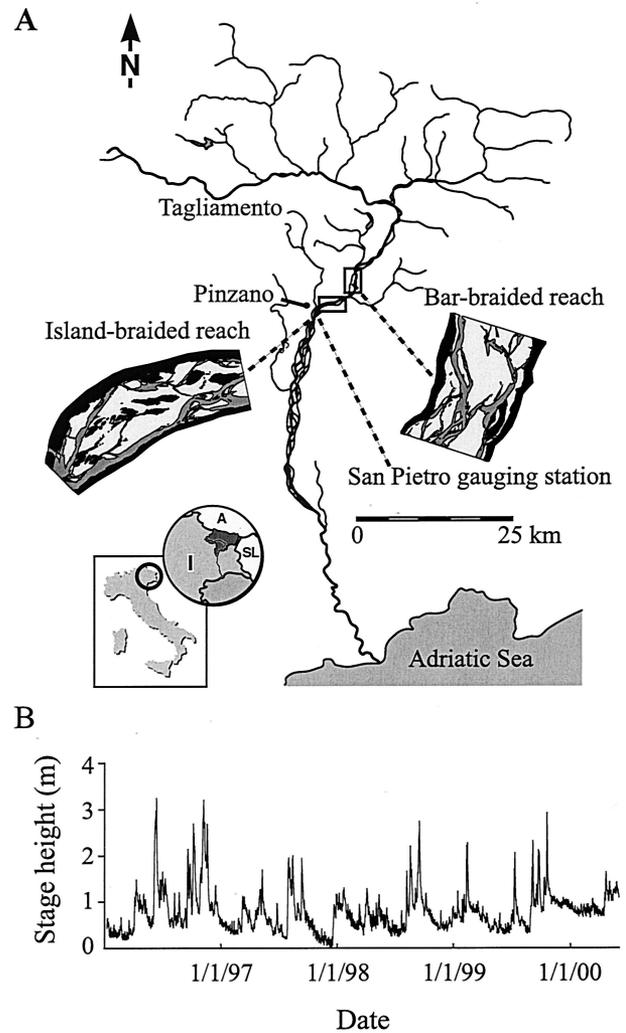


Figure 1. (A) Location of the Tagliamento catchment, with insets showing the configuration of the bar-braided and island-braided reaches in May 2000. In the insets, black indicates floodplain forest and vegetated islands; dark gray indicates surface water; light gray indicates exposed alluvial gravel. (B) Stage height for the Tagliamento River at the San Pietro gauging station 1.5 km downstream of the island-braided reach.

river kilometer 81 and upstream of a narrow bedrock constrained knick point at Pinzano (Figure 1A). Total surface area was 143 ha, length was 1.8 km, and the active floodplain width was 0.8 km. The reach included a complex channel network with approximately 20 vegetated islands. In addition to main and secondary channels, many alluvial channels, backwaters, and isolated water bodies occurred in both reaches. Exposed sediments in the form of lateral or mid-channel gravel bars represented the largest proportion of landscape cover elements.

Table 1. Morphological Characteristics of a Bar-braided and an Island-braided Reach of the Tagliamento River in Northeast Italy (at a Water Level of 0.95 m) and Dates and Water Levels at Which Maps Were Made

	Bar-braided Reach		Island-braided Reach	
Length (km)	1.5		2.5	
Area of active floodplain (ha)	103		143	
Area water (%)	35		39.1	
Area islands (%)	3.1		10.6	
Area exposed sediments (%)	61.9		50.4	
	Water Level (m)	Date	Water Level (m)	Date
	0.15	10 Dec 01	0.74	10 Jan 00
	0.74	09 Jan 00	1.02	12 Nov 99
	1.00	15 Nov 99	1.23	01 Nov 99
	1.20	03 Nov 99	1.50	28 Oct 99
	1.46	04 Apr 00	1.65	27 Oct 99
	1.65	15 Oct 00	2.35	26 Oct 99

METHODS

Geographical data were collected using a differential global positioning system (DGPS) rover unit (TCS1, Trimble, Sunnvale, California, USA). All shorelines were delineated in situ by walking along them, carrying the DGPS receiver. Positions were recorded at 5-sec intervals and later postcorrected using base station data to obtain a precision of 0.3 m or less. The base station was located less than 5 km from both study reaches and remained stationary during all surveys to record variations in triangulation due to satellite movement.

Data were collected at different river stage heights following a major flood that started on 26 October 1999. Between 27 October and 15 November 1999, data were collected on five dates in the island-braided reach and on two dates in the bar-braided reach (Table 1). The dangerous and time-consuming task of mapping during flood conditions forced us to focus our attention on one reach at a time. Both reaches were mapped again in January 2000 during a period of lower water level (0.74 m). To obtain comparable data for the bar-braided reach, we carried out two additional mapping sessions there in April and October 2000, when water levels reached values comparable to those for which we mapped the island-braided reach. Finally, in December 2001, we mapped the bar-braided reach at low flow (0.10 m). For three of the mapped water levels, the configuration and extent of inundation are shown in oblique photographs (Figure 2).

The water levels covered by these surveys ranged between 2.35 m and 0.74 m at the gauging station of San Pietro (Figure 1A) for the island-braided reach

and between 1.65 m and 0.15 m for the bar-braided reach. The mean water level at the San Pietro gauge is approximately 0.8 m. Due to the frequently changing and complex bed morphology, cross-sectional channel profiles change rapidly preventing a reliable estimation of discharge (see Campolo and others 1999; Gurnell and others 2000a). Consequently, water level rather than discharge was used in our analysis. Water-level data were provided by the Direzione Regionale dell' Ambiente and the Autorita di Bacino dei Fiume Isonzo, Tagliamento, Livenza.

We used ARC-INFO (Environmental Systems Research Institute, Redlands, California, USA) software to generate maps and to determine complexity parameters from these maps. Sinuosity and braiding indexes (Friend and Sinha 1993), number of nodes, and number and total area of floodplain ponds were determined. Nodes are ecotones within aquatic systems defined as the intersections between water body thalwegs (Arscott and others 2000). Channel nodes are intersections between channel thalwegs with both upstream and downstream connections. The total number of nodes also includes intersections with and within water bodies with only upstream or only downstream connections. Upstream surface hydrological connectivity (SC) was measured from all maps following Malard and others (2000), by dividing the area of channels fed by surface water (A_c) by the total area of channels with surface flow (A). A Spearman rank-order correlation was performed to investigate which parameters best described the relationship between water level and complexity.

Additionally, we determined total inundated area and shoreline length from each map. An overlay function was used to combine all information into

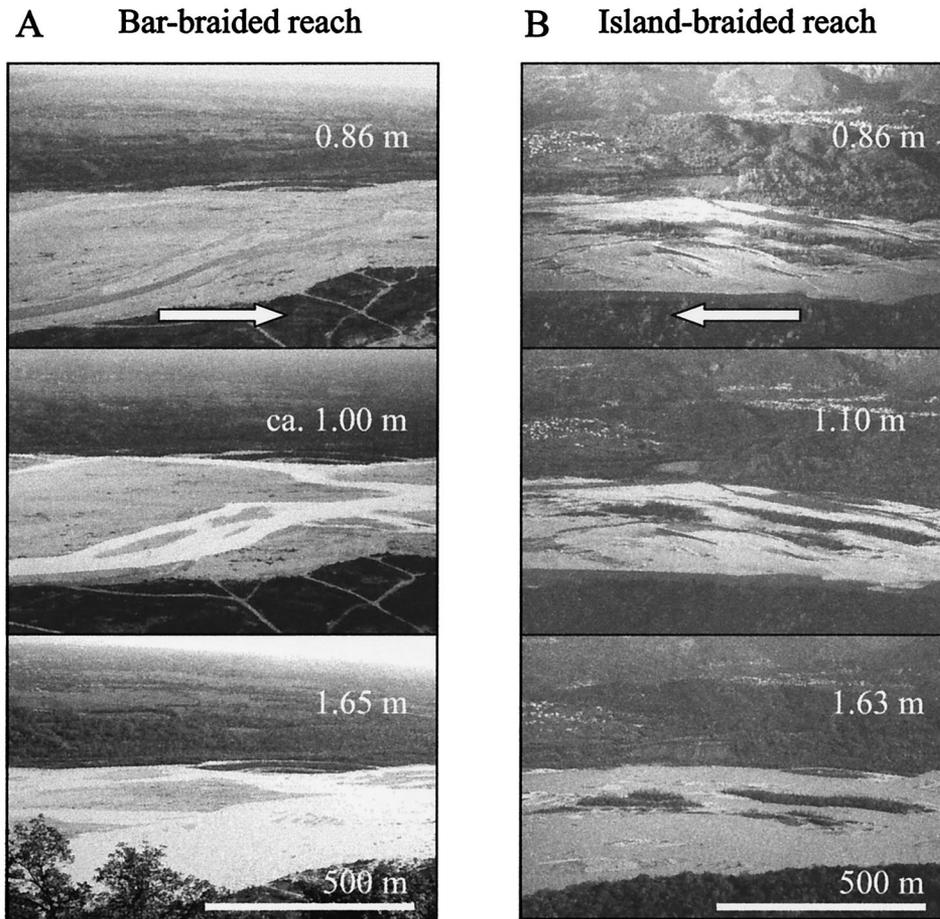


Figure 2. Oblique photographs of **A** the bar-braided and **B** the island-braided reach taken at low, mean, and high water levels. Arrows indicate the flow direction. (Photos: C. Yoshimura and D. van der Nat.)

inundation maps, which showed the extent of inundation for a given water level for each floodplain. The largest vertical elevation differences found in topographic transects through the study reaches were about 2.5 m (see Gurnell and others 2000b). Shoreline length is expressed in both meters per hectare of active floodplain and in kilometer per river-kilometer. Inundated area is expressed as the proportion (%) of the active floodplain covered by water.

Relative inundation of the active floodplain was arcsine square-root-transformed and regressed against water level and reach in a linear model (Statistica 5.1; Statsoft Inc., Tulsa, Oklahoma, USA). We assumed that at maximum water-level shoreline length would equal the length of the border between the active floodplain and the adjacent riparian forest. This assumption made a second-order polynomial function the most logical regression curve. Inundated area was regressed in a linear model against water level squared, water level, and reach.

We used the observed relationship as a predictive model and converted 5 years of water-level data from the San Pietro gauging station to a time series

of relative inundation and shoreline length. Consequently, a duration curve for the degree of inundation and a frequency distribution of shoreline length were generated from the same data.

RESULT

Sinuosity was low and constant (1.0 to 1.24) across water levels for both reaches (Table 2). The braiding index reached values as high as 6.87. The Spearman rank-order correlation showed that both braiding index and upstream surface hydrologic connectivity showed a significant positive relationship with water level. The total area covered by ponds was inversely related to water level. The total number of nodes was positively related to the shoreline length. Channel nodes, sinuosity, and number of ponds were not related to either water level or shoreline length.

In the bar-braided reach, more than 60 percent of the total active floodplain area was inundated at the highest mapped water level (1.65 m). During the falling limb of the hydrograph, the degree of inundation decreased monotonously to about 10% at the lowest mapped water level (0.15 m). During the de-

Table 2. Complexity Descriptors: Sinuosity, Braiding Index, Channel Nodes, Total Nodes, Number of Ponds, Total Area of Ponds, Relative Inundation, Upstream Surface Hydrologic Connectivity, and Shoreline Length for the Bar-braided and Island-braided Reaches at All Mapped Water Levels

Reach	Stage (m)	Sinuosity	Braiding Index	Channel Nodes	Total Nodes	Ponds (n)	Ponds A (m ²)	Rel. Inun. %	SC	Shoreline (m ha ⁻¹)
Bar-braided	0.15	1.24	2.17	24	33	12	14,047	10.8	0.83	108.0
	0.74	1.09	1.57	12	42	7	3834	12.6	0.43	145.6
	1.00	1.11	5.40	64	99	21	6164	22.6	0.83	212.8
	1.20	1.08	5.82	51	93	8	2404	29.5	0.91	214.0
	1.46	1.08	4.99	24	60	9	3649	41.6	0.92	195.2
	1.65	1.02	6.87	31	54	1	52	58.7	0.99	160.6
Island-braided	0.74	1.00	3.60	34	48	22	7542	24.3	0.84	178.4
	1.02	1.00	4.41	50	83	33	12,411	29.4	0.84	212.6
	1.23	1.00	4.04	36	78	22	10,491	35.2	0.92	194.5
	1.50	1.00	4.94	41	96	22	1112	48.5	0.91	213.4
	1.65	1.00	4.93	16	46	11	2216	57.5	0.97	182.6
	2.35	1.08	6.26	54	62	4	1010	78.2	1.00	157.8

SC, upstream surface hydrologic connectivity.

cline, the configuration of the channel network changed from being dominated by upstream-and downstream-connected channels to a heterogeneous system of only downstream-connected and isolated water bodies (Table 2 and Figure 3A). In the bar-braided reach, complete active floodplain inundation was estimated to occur at water levels at or above 2.5 m.

Inundated area also decreased monotonously with receding water level in the island-braided floodplain. At the highest mapped water level (2.35 m), almost 80% of the active floodplain was inundated. At this water level, only vegetated islands and very high gravel bars protruded above the water in the active floodplain. At the lowest mapped water level (0.74 m), 20% of the active floodplain was covered by water. The configuration of the floodplain consisted of a matrix of exposed sediments with numerous isolated water bodies and primarily downstream-connected channels. Several upstream-connected channels remained, however, even at the lowest mapped water levels (Figure 2 and Figure 3B). In the island-braided reach, complete active floodplain inundation was estimated to occur at water levels at or above 3.0 m.

Linear regression of the arcsine square root of inundation with water level and reach indicated that the effect of the factor reach was insignificant ($P > 0.70$) (Table 3). We therefore excluded this factor from further analysis and combined the inundation data for both reaches (Figure 4A). A new

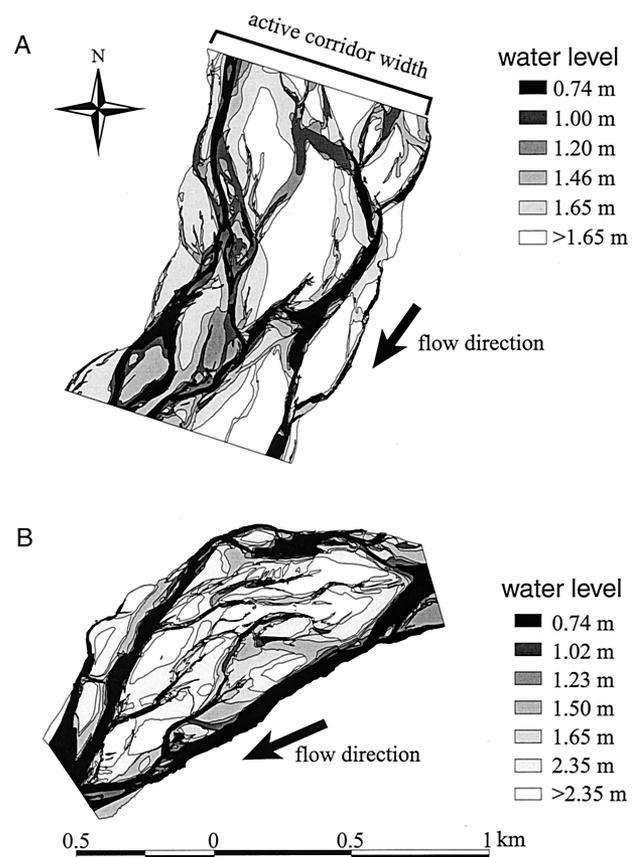


Figure 3. Inundation patterns for (A) a bar-braided and (B) an island-braided reach of the Tagliamento River. Water levels correspond to stage height readings from the San Pietro gauging station.

Table 3. Linear Regression Models for Dependent Variables (Arcsine Square Root of Inundation and Shoreline Length) and Independent Variables (Stage Height, Squared Stage Height, and Reach) for a Bar- and an Island-braided Reach of the Tagliamento River

Arcsine Square Root Relative Inundation				Shoreline Length (m ha ⁻¹)			
		Beta	P			Beta	P
Two variables	Stage	0.97	2.9 10⁻⁷	Three variables	Stage ²	-2.69	3.96 10⁻³
	Reach	-0.02	>0.70		Stage	1.84	2.72 10⁻²
One variable	Stage	0.96	7.6 10⁻⁸		Reach	0.23	0.10
Regression $y = 0.49x + 0.07$ $P < 0.00001$, $R^2_{adj} = 0.910$				Two variables			
					Stage ²	-2.73	1.52 10⁻⁴
					Stage	2.09	1.20 10⁻³
				Regression $y = 87.825 - 65.849x^2 + 169.829x$ $P < 0.00009$, $R^2_{adj} = 0.783$			

Beta and probability values for significant variables are set in boldface type.

linear regression model with water level as the only independent variable showed a significant effect of water level on degree of inundation ($P < 7.6 \cdot 10^{-8}$). The linear regression model was highly significant ($P < 0.00001$, $R^2_{adj} = 0.91$), (Table 3) and was described by the following equation:

$$y = 0.49x + 0.07$$

where y represents the arcsine square root of inundation and x represents water level (m).

Shoreline lengths ranged from 28 m ha⁻¹ (2.1 km km⁻¹) to 214 m ha⁻¹ (16.3 km km⁻¹) in the bar-braided reach. Shoreline length peaked at intermediate water levels between 1.0 and 1.2 m (Figure 4B). Shoreline length in the island-braided reach showed a similar range. The minimum value of 37 m ha⁻¹ (3.0 km km⁻¹) occurred at complete active floodplain inundation. The maximum of 212 m ha⁻¹ (17.3 km km⁻¹) occurred at water levels of between 1.0 and 1.65 m (Figure 4B).

A linear regression model with water level, squared water level, and reach as independent variables and shoreline length as the dependent variable indicated that the effect of reach was insignificant ($P = 0.10$), (Table 3). Hence, data for both reaches were combined and the regression was repeated without reach as an independent variable. Both water level and squared water level were found to be highly significant factors ($P = 1.20 \cdot 10^{-3}$ and $P = 1.52 \cdot 10^{-4}$, respectively). The second-order polynomial regression curve (Figure 4B) was highly significant ($P < 0.00009$, $R^2_{adj} = 0.783$) and was described by the following function:

$$y = 87.825 - 65.849x^2 + 169.829x$$

where y represents shoreline length (m ha⁻¹) and x represents water level (m).

Relationships among water level, inundated area, and shoreline length were used to convert water-level data for the period between January 1996 and May 2000 into a time series for inundated area and shoreline length (compare Figure 5 with Figure 1B). Mapped water levels ranged from 0.15 m to 2.35 m, and water-level data for 1996–2000 ranged from 0.0 m to 3.24 m.

Due to the linearity of the model, the simulated curve for inundated area strongly resembled the hydrograph (compare Figure 1A with Figure 5A). Predicted shoreline lengths were high, averaging 171 m ha⁻¹ (12.8 km km⁻¹). Short-term reductions (less than 3 days for each event) in shoreline length occurred during major flood events.

A duration curve of relative active floodplain inundation was used to illustrate inundation time during the 1996–2000 period (Figure 6). The rate of increase in inundation was relatively stable during most of the time series, with sharp increases during only about 10% of the time, when water levels were greater than 1.3 m (Figure 6). A frequency distribution of simulated shoreline length is also plotted in Figure 6. Shoreline length was low at minimum and at maximum water levels. Maximum shoreline length occurred at a water level of approximately 1.3 m, which was exceeded 10% of the time. Simulated shoreline length was high (150–200 m ha⁻¹, 11–15 km km⁻¹) (see also Figure 5B) for most of the time (more than 90%).

DISCUSSION

The importance of the flood pulse for the ecology of floodplain ecosystems has been well documented (for example, Junk and others 1989; Bayley 1991; Tockner and others 2000b). Information about in-

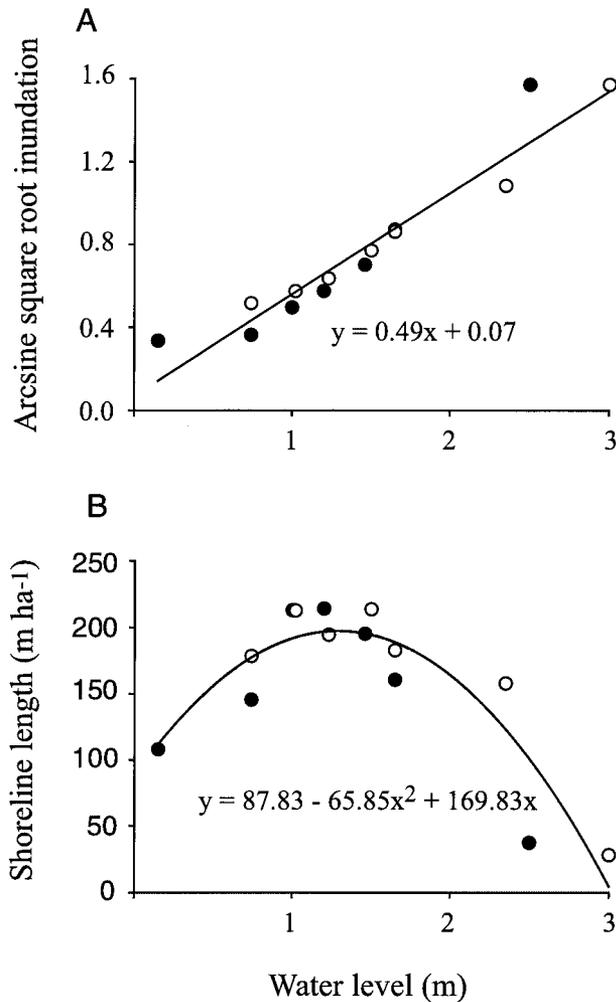


Figure 4. (A) Linear regression of relative floodplain inundation (arcsine square-root-transformed) versus water-level readings from the San Pietro gauging station. (B) Second-order polynomial regression of shoreline length versus water-level readings. Solid circles represent the bar-braided reach; open circles represent the island-braided reach.

undation dynamics across a range of water levels is needed to better understand flow and flood dynamics as factors shaping floodplains and their ecology (Benke and others 2000; Tockner and others 2000b, 2002b). The present paper shows that availability of aquatic habitats and the ecologically important aquatic-terrestrial interface (Naiman and Décamps 1997; Ward and others 1999b) are influenced by frequent minor water-level fluctuations. This supports the hypothesis that in addition to the flood pulse, flow pulses below bank-full also constitute a major physical variable determining ecological processes in floodplain systems (Malard and others 1999; Tockner and others 2000b).

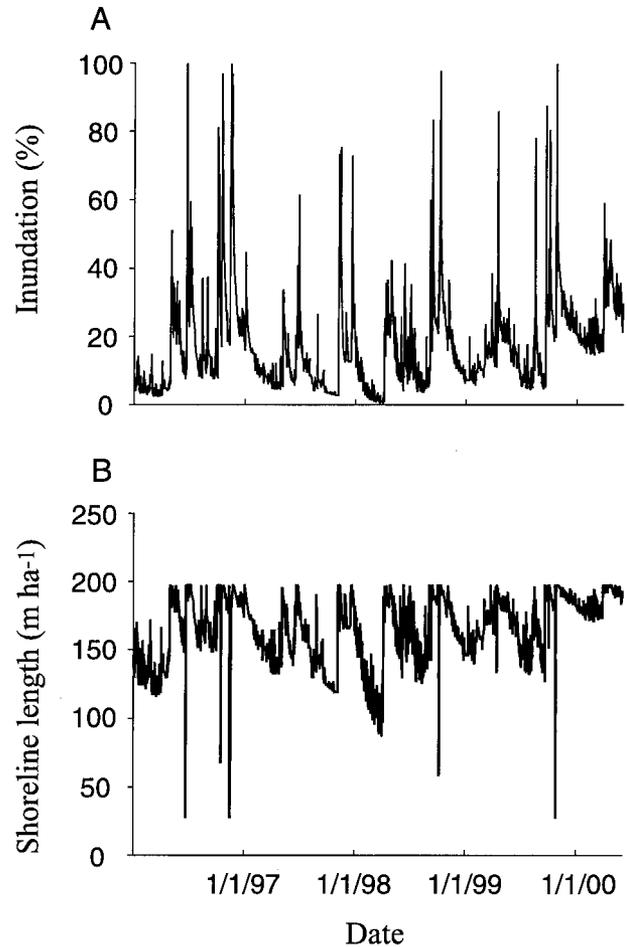


Figure 5. (A) Predicted inundated area and (B) predicted shoreline length for the period January 1996 through May 2000 for a bar-braided and an island-braided reach of the Tagliamento River. Because the regressions for the bar-braided and the island-braided reaches were not significantly different, data from both reaches are combined here.

This study has shown complex inundation patterns to exist within the active floodplain of a large semi-natural Alpine river. Most of the time, the aquatic component of the floodplain was a mosaic of braided channels (primary, secondary, and tertiary), alluvial channels, and isolated water bodies. An increase in water level temporarily shifted this configuration toward a dominance by channels. Decreases in water level shifted the configuration toward isolated and downstream-connected water bodies. The larger number of vegetated islands (Ward and others 1999a) and large woody debris deposits (Gurnell and others 2000b; van der Nat and others 2001) in the island-braided reach resulted in a higher abundance of isolated water bodies such as scour holes (Table 2). These aquatic

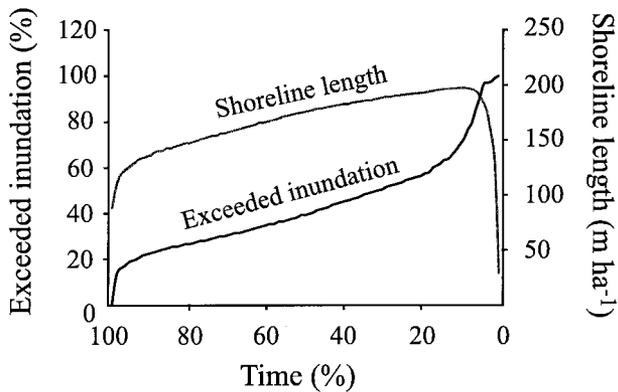


Figure 6. Duration curve (percentage of time at which value equaled or exceeded) for floodplain inundation and a frequency distribution of shoreline length in two braided floodplains of the Tagliamento River. Because the regressions for the bar-braided and the island-braided reaches were not significantly different, data from both reaches are combined here.

islands, temporary or permanent, are important habitats and refuges for aquatic invertebrates (U. Karaus personal communication; Homes and others 1999), fishes (Galat and others 1997, 1998), and amphibians (Morand and Joly 1995; Griffiths 1997; Tockner and others, unpublished).

Although the bar- and island-braided reaches differed considerably in morphology, their inundation dynamics and shoreline lengths were similar. The sinuosity of the main channel in both reaches remained low and constant (Table 2). In complex braided systems, sinuosity is not as suited to describe shoreline complexity as it is in meandering or single channel systems. In the Danube downstream of Vienna, sinuosity was used to quantify shoreline complexity within the main stem (Schiemer and others 2001). In our system, total shoreline length, the braiding index, upstream surface hydrologic connectivity (SC), and total area of isolated water bodies best described the relationship between water level and complexity. The positive relationship among braiding index, SC, and water level indicates a potentially increasing complexity of the aquatic component of the active floodplain with rising water levels (up to a certain point). However, this increase is partly counteracted by a decrease in complexity due to a diminishing area of isolated water bodies.

The water level above which the most rapid morphological changes to the floodplain occur in the Tagliamento River was estimated to be three times the average stage height (Arscott 2002). The average stage height during the period of simulation

was 0.79 m. According to our model, considerable morphological changes would thus occur at inundations of 89% and more. Five such events have occurred during the period of simulation (Figure 5A)

The linear relationship between water level and inundated area in this temperate unregulated river concurs with that found by Benke and others (2000) for the subtropical Ogeechee River (southeastern United States). In contrast, in the hydrologically dynamic but morphologically regulated Danube floodplain of the Alluvial Zone National Park, Austria, inundated area increased stepwise with increasing water level (Tockner and others 2000a). Therefore, below mean flow, inundated area of the floodplain increased monotonously but slowly through seepage inflow.

Above mean water level, overbank flow resulted in a sudden increase of the inundated area. The relationship between water level and inundation was also documented in tropical rivers with predictable flooding regimes. For example, in a Pantanal wetland of South America, a linear relationship was found between monthly estimates of inundated area and the flood stages of the previous 2 months (Hamilton and others 1996). Similar observations from the Amazon River revealed a second-order polynomial relationship between monthly estimates of inundated area and river stage (Sippel and others 1998).

The second-order polynomial relationship between water level and shoreline length was significant and similar to the unimodal pattern found by Tockner and others (2000a) for the Danube (Austria). The maximum shoreline length found there (122 m ha^{-1} , 8.5 km km^{-1}) was considerably lower than the maximum found in this study (213 m ha^{-1} , 17.3 km km^{-1}).

Applying our predictive regressions from 1 year of data to 5 years of water-level data creates several complications. In a system that is morphologically dynamic, as the Tagliamento River, it is possible that channel-bed elevations change frequently. Changes in bed elevation would result in a change in the stage–discharge relationship. However, there are indications that this relationship does not alter too dramatically in our system. Analysis of the hydrograph by Arscott and others (2000) indicated that the yearly average stage height decreased 39 cm over the period of 1982–99. A decline of 2 cm per year should not have too-serious implications for the stage–discharge relationship over a 5-year period. Second, the gauging station at San Pietro is located at a stable bedrock constriction, making changes in the stage–discharge relationship less

Table 4. Shoreline Length (in km km^{-1} , Around Mean Water Level) for Regulated Rivers and Free-Flowing Rivers

River	Region	Morphology	Shoreline length (km km^{-1})	Reference
Tagliamento	NE Italy	Free-flowing	14.7	Present study
Tagliamento Headwater	NE Italy	Free-flowing	7.9	Arcott and others 2000
Danube	Austria	Semi-natural	8.5	Tockner and others 2000a
Rhône	Switzerland	Channelized	2.1	Tockner and others 2002
Piave	NE Italy	Regulated	$\sim 3^a$	Surian 1999
Val Roseg	Switzerland	Free-flowing	16.5	Malard and others 1999
Willamette	Oregon, USA	Prior to regulation	>10	Cited in Amoros (1996)
Willamette	Oregon, USA	After regulation	>2.6	Cited in Amoros (1996)
Gearagh	Ireland	Free-flowing	26^a	Brown and others 1995
Zaire	Central Africa	Free-flowing	26^a	Cited in Brown (1995)
Rakaia	New Zealand	Free-flowing	28^a	Cited in Brown (1995)
Waimakariri	New Zealand	Free-flowing	8^a	Cited in Brown (1995)

^aValues extrapolated from braiding index.

likely to occur. Third, large flood events dramatically change the configuration of the active floodplain in the Tagliamento. In our reaches, as much as 45% of all aquatic habitat was turned over by a large flood pulse (Arcott 2002). However, at the same time, the composition of landscape elements (for example, water, gravel bars) in the active floodplain remains more or less the same. Flood pulses create as many new channels, alluvial channels, backwaters, and pools as they destroy. Had the flood pulses altered the stage–discharge relationship, maps made at the same water level before and after a flood pulse would not have shown similar compositions.

Some water-level values from the 5-year simulation were outside the range of actually measured values. Because we have extrapolated in the predictive model, care has to be taken in interpreting model outcomes. However, the simulation of inundated area in the study reaches did show a number of important trends. During 50% of the time, inundated area was lower than 30% (Figure 6). Consequently, during most of the year, the active floodplain is a mosaic of aquatic patches within a matrix of exposed sediments. Complete or near-complete inundation of the active floodplain occurred three to four times per year; at these times, all water bodies were connected by surface-water flow, allowing mixing of populations that were isolated for much of the year. Animals such as young fish need these large inundations to disperse from their spawning grounds to other parts of the river (Fernandes 1997). Additionally, members of various

fish families in temperate European and North American rivers require flowing water during some life stages (Galat and Zweimüller 2001).

Shoreline length remained high most of the time, in contrast to highly regulated rivers that have much lower shoreline lengths (Table 4). Minimum shoreline lengths, comparable to the values seen for regulated rivers throughout the year, only occur during large spates. With the decreasing availability of free-flowing rivers, the shoreline interface has become an endangered fluvial landscape element (for example, Pinay and others 1990).

The fact that braided reaches of the Tagliamento River sustain an abundance of shoreline habitat throughout the year is of considerable ecological importance. Shorelines provide specific habitats for a variety of specialized biota (for example, Salo and others 1986; Décamps and others 1987; Risser 1990; Reich 1994; Wintersberger 1996). High abundance of shoreline is important for sustaining riparian biodiversity (Risser 1990; Nilsson and others 1997; Maiolini and others 1998; Luken and Bezold 2000). It is also important for facilitating biotic and abiotic interactions between the aquatic and the terrestrial zones of the floodplain (Bardgett and others 2001; Ward and Wiens 2001). The fact that these habitats are important to rare alluvial flora and fauna makes preservation of our remaining free-flowing rivers a significant priority.

ACKNOWLEDGMENTS

We thank the subject editor Dr. Naiman and two anonymous reviewers for comments that resulted

in considerable improvements to this paper. We also thank David B. Arscott, Michael T. Monaghan, and Sophie Karrenberg van der Nat for fruitful discussions and suggestions made to earlier versions of this manuscript. We are grateful to several people who helped with field logistics, especially Diego Nebuloni and Grazia Varra. Special thanks to Mr. Alberto Deana of the Direzione Regionale dell' Ambiente and Mr. Francesco Baruffi of the Autorita di Bacino dei Fiume Isonzo, Tagliamento, Livenza, for providing hydrological data. Grant 0-20572-98 from the Forschungskommission of the Eidgenössische Technische Hochschule Zürich supported this research.

REFERENCES

- Amoros C, Gilbert J, Greenwood MT. 1996. Interactions between units of the fluvial hydrosystem. In: Petts GE, Amoros C, editors. *Fluvial hydrosystems*. London: Chapman & Hall. p 184–210.
- Arscott DB. 2002. Habitat heterogeneity and aquatic invertebrates along an Alpine floodplain river [thesis]. Zürich: Eidgenössische Technische Hochschule.
- Arscott DB, Tockner K, Ward JV. 2000. Aquatic habitat diversity along the corridor of an Alpine floodplain river (Fiume Tagliamento, Italy). *Arch Hydrobiol* 149:679–704.
- Bardgett RD, Anderson JM, Behan-Pelletier V, Brussaard L, Coleman DC, Moldenke A, Schimel JP, Wall DH. 2001. The influence of soil biodiversity on hydrological pathways and the transfer of materials between terrestrial and aquatic ecosystems. *Ecosystems* 4:421–9.
- Bayley PB. 1991. The flood pulse advantage and the restoration of river floodplain systems. *Reg Rivers Res Manage* 6:75–86.
- Benke AC. 2001. Importance of flood regime to invertebrate habitat in an unregulated river–floodplain ecosystem. *J North Am Benthol Soc* 20:225–40.
- Benke AC, Chaubey I, Milton Ward G, Dunn EL. 2000. Flood pulse dynamics of an unregulated river floodplain in the southeastern U.S. coastal plain. *Ecology* 81:2730–41.
- Bonn A, Hagen K, Wohlgemuth–von Reiche W. 2002. The significance of flood regimes for carabid beetles and spider communities in riparian habitats—a comparison of three major rivers in Germany. *Reg Rivers Res Manage* 18:43–64.
- Brasington J, Rumsby BT, McVey RA. 2000. Monitoring and modelling morphological change in a braided gravel-bed river using high resolution GPS based survey. *Earth Surface Processes Landforms* 25:973–90.
- Brown AG, Stone P, Harwood K. 1995. The biogeomorphology of a wooded anastomosing river: the Gearagh on the River Lee in county Cork, Ireland. Occasional paper 32. Leicester (England): Department of Geography, University of Leicester.
- Campolo M, Andreussi P, Soldati A. 1999. River flood forecasting with a neural network model. *Water Resources Res* 35:1191–7.
- Décamps H, Joachim J, Lauga J. 1987. The importance for birds of the riparian woodlands within the alluvial corridor of the River Garonne, S.W. France. *Reg Rivers Res Manage* 1:301–16.
- de Vries JJ. 1995. Seasonal expansion and contraction of stream networks in shallow groundwater systems. *J Hydrol* 170:15–26.
- Fernandes CC. 1997. Lateral migration of fishes in Amazon floodplains. *Ecol Freshwater Fish* 6:36–44.
- Fisher SG, Grimm NB, Marti E, Holmes RM, Jones JB. 1998. Material spiralling in stream corridors: a telescoping ecosystem model. *Ecosystems* 1:19–34.
- Friend PF, Sinha R. 1993. Braiding and meandering parameters. In: Best JL, Bristow JL, editors. *Braided rivers*. London: Geological Society. p 105–11.
- Galat DL, Fredrickson LH, Humburg DD, Bataille KJ, Bodie JR, Dohrenwend J, Gelwicks GT, Havel JE, Helmers DL, Hooker JB, and others. 1998. Flooding to restore connectivity of regulated, large-river wetlands: natural and controlled flooding as complementary processes along the lower Missouri River. *BioScience* 48:721–33.
- Galat DL, Kubisiak JF, Hooker JB, Sowa LM. 1997. Geomorphology, distribution and connectivity of lower Missouri River floodplain waterbodies scoured by the flood of 1993. *Verh Int Ver Limnol* 26:869–78.
- Galat DL, Zweimüller I. 2001. Conserving large-river fishes: is the *highway analogy* an appropriate paradigm? *J North Am Benthol Soc* 20:266–79.
- Gilvear DJ, Waters TM, Milner AM. 1995. Image analysis of aerial photography to quantify changes in channel morphology and instream habitat following placer mining in interior Alaska. *Freshwater Biol* 34:389–98.
- Griffiths RA. 1997. Temporary ponds as amphibian habitats. *Aqua Conserv Mar Freshwater Ecosyst* 7:119–26.
- Gurnell AM, Petts GE, Hannah DM, Edwards PJ, Kollmann J, Ward JV, Tockner K. 2000a. Large wood retention in river channels: the case of the Fiume Tagliamento, Italy. *Earth Surface Processes Landforms* 25:255–75.
- Gurnell AM, Petts GE, Hannah DM, Smith BPG, Edwards PJ, Kollmann J, Ward JV, Tockner K. 2000b. Wood storage within the active zone of a large European gravel-bed river. *Geomorphology* 34:55–72.
- Hamilton SK, Sippel SJ, Melack JM. 1996. Inundation patterns in the Pantanal wetland of South America determined from passive microwave remote sensing. *Arch Hydrobiol* 137:1–23.
- Homes V, Hering D, Reich M. 1999. The distribution and macrofauna of ponds in stretches of an alpine floodplain differently impacted by hydrological engineering. *Reg Rivers Res Manage* 15:405–17.
- Hughes FMR, Rood SB. 2001. Floodplains. In: Warren A, French JR, editors. *Habitat conservation: managing the physical environment* Chichester (England): Wiley. p 105–21.
- Junk WJ, Bayley PB, Sparks RE. 1989. The flood pulse concept in river–floodplain systems. *Canadian Special Publications for Fisheries and Aquatic Sciences*. 106:110–127.
- Lesack LFW, Melack JM. 1995. Flooding hydrology and mixture dynamics of lake water derived from multiple sources in an Amazon floodplain lake. *Water Resources Res* 31:329–45.
- Luken JO, Bezold TN. 2000. Plant communities associated with different shoreline elements at Cave Run lake, Kentucky. *Wetlands* 20:479–86.
- Maiolini B, Franceschini A, Boscaini A. 1998. The role of invertebrate communities as indicators of environmental characteristics of European river margins. In: Joyce CP, Wade M, editors. *European wet grasslands: biodiversity, management and research* Chichester (England): Wiley. p 151–62.

- Malard F, Tockner K, Ward JV. 2000. Physico-chemical heterogeneity in a glacial riverscape. *Landscape Ecol* 15:679–95.
- Malard F, Tockner K, Ward JV. 1999. Shifting dominance of sub-catchment water sources and flow paths in a glacial floodplain, Val Roseg, Switzerland. *Arctic Antarctic Alpine Res* 31:135–50.
- Mertes LAK. 1997. Documentation and significance of the perirheic zone on inundated floodplains. *Water Resources Res* 33:1749–62.
- Morand A, Joly P. 1995. Habitat variability and space utilization by the amphibian communities of the French Upper-Rhone floodplain. *Hydrobiol* 300/301:249–57.
- Mosley MP. 1982. Analysis of the effect of changing discharge on channel morphology and instream uses in a braided river, Ohau River, New Zealand. *Water Resources Res* 18:800–12.
- Müller N. 1995. River dynamics and floodplain vegetation and their alterations due to human impact. *Arch Hydrobiol* 101:477–512.
- Naiman RJ, Décamps H. 1997. The ecology of interfaces: riparian zones. *Annu Rev Ecol Syst* 28:621–58.
- Newbold JD, Mulholland PJ, Elwood JW, O'Neill RV. 1982. Organic carbon spiralling in stream ecosystems. *Oikos* 38:266–72.
- Nilsson C, Jansson R, Zinko U. 1997. Long-term responses of river-margin vegetation to water-level regulation. *Science* 276:798–800.
- Petts GE, Moller H, Roux AL, editors. 1989. Historical changes of large alluvial rivers, Western Europe. Chichester, (England): Wiley.
- Pinay G, Décamps H, Chauvet E, Fustec E. 1990. Functions of ecotones in fluvial systems. In: Naiman RJ, Décamps H, editors. The ecology and management of aquatic-terrestrial ecotones. Casterton Hall (UK): Parthenon. p 141–70.
- Poff LN, Ward JV. 1989. Implications of streamflow variability and predictability for lotic community structure: a regional analysis of streamflow pattern. *Can J Fish Aquat Sci* 46:1805–18.
- Reich M. 1994. Kies- und schotterreiche Wildflußlandschaften—primäre Lebensräume des Flußregenpfeifers (*Charadrius dubius*). *Vogel Umwelt* 8:43–52.
- Rempel LL, Richardson JS, Healey MC. 1999. Flow refugia for benthic macroinvertebrates during flooding of a large river. *J North Am Benthol Soc* 18:34–48.
- Risser PG. 1990. The ecological importance of land-water ecotones. In: Naiman RJ, Décamps H, editors. The ecology and management of aquatic-terrestrial ecotones. Casterton Hall (UK): Parthenon. p 7–22.
- Salo J, Kalliola R, Häkkinen I, Mäkinen Y, Niemelä P, Puhakka M, Coley PD. 1986. River dynamics and the diversity of Amazon lowland forest. *Nature* 322:254–8.
- Schiemer F, Keckeis H, Reckendorfer W, Winkler G. 2001. The “inshore retention concept” and its significance for large rivers. *Arch Hydrobiol Suppl* 135:509–16.
- Sippel SJ, Hamilton SK, Melack JM, Novo EMM. 1998. Passive microwave observations of inundation area and the area/stage relation in the Amazon River floodplain. *Int J Remote Sens* 19:3055–74.
- Sparks RE, Bayley PB, Kohler SL, Osborne LL. 1990. Disturbance and recovery of large floodplain rivers. *Environ Manage* 14:699–709.
- Spink A, Sparks RE, Oorschot van M, Verhoeven JTA. 1998. Nutrient dynamics of large river floodplains. *Reg Rivers Res Manage* 14:203–16.
- Stanley EH, Fisher SG, Grimm NB. 1997. Ecosystem expansion and contraction in streams. *BioScience* 47:427–35.
- Surian N. 1999. Channel changes due to river regulation: the case of the Piave River, Italy. *Earth Surface Processes Landforms* 24:1135–51.
- Tockner K, Baumgartner C, Schiemer F, Ward JV. 2000a. Biodiversity of a Danubian floodplain: structural, functional and compositional aspects. In: Gopal B, Junk WJ, Davis JA, editors. Biodiversity in wetlands: assessment, function and conservation. Leiden: Backhuys. p 141–59.
- Tockner K, Malard F, Ward JV. 2000b. An extension of the flood pulse concept. *Hydrol Processes* 14:2861–83.
- Tockner K, Ward JV, Stanford JA. 2002. Riverine flood plains: present state and future trends. *Environ Conserv*. Forthcoming.
- van der Nat D, Tockner K, Edwards PJ, Ward JV. 2001. Quantification of large woody debris in large floodplain rivers: an area-based approach using differential GPS and GIS. *Verh Int Ver Limnol*. Forthcoming.
- Vannote RL, Minshall GW, Cummins KW, Sedell JR, Cushing CE. 1980. The river continuum concept. *Can J Fish Aquat Sci* 37:130–7.
- Warburton J, Davies TRH, Mandl MG. 1993. A meso-scale investigation of channel change and floodplain characteristics in an upland braided gravel-bed river. In: Best JL, Bristow CS, editors. Braided rivers Geological Society, London p 241–55.
- Ward JV, Malard F, Tockner K. 2002a. Landscape ecology: a framework for integrating pattern and process in river corridors. *Landscape Ecol*. 17(Supl 1):35–45.
- Ward JV, Stanford JA. 1983. The serial discontinuity concept of lotic ecosystems. In: Fontaine TD, Bartell SM, editors. Dynamics of lotic ecosystems. Ann Arbor (MI): Ann Arbor Science. p 29–42.
- Ward JV, Stanford JA. 1995. The serial discontinuity concept: extending the model to floodplain rivers. *Reg Rivers Res Manage* 10:159–68.
- Ward JV, Tockner K, Arscott DB, Claret C. 2002b. Riverine landscape diversity. *Freshwater Biol*. 47:517–40.
- Ward JV, Tockner K, Edwards PJ, Kollman J, Bretschko G, Gurnell AM, Petts GE, Rossaro B. 1999a. A reference river system for the Alps: the Fiume Tagliamento. *Reg Rivers Res Manage* 15:63–75.
- Ward JV, Tockner K, Schiemer F. 1999b. Biodiversity of floodplain river ecosystems: ecotones and connectivity. *Reg Rivers Res Manage* 15:125–39.
- Ward JV, Wiens JA. 2001. Ecotones of riverine ecosystems: role and typology, spatio-temporal dynamics, and river regulation. *Ecohydrol Hydrobiol* 1:25–36.
- Wintersberger H. 1996. Spatial resource utilization and species assemblages of larval and juvenile fish. *Arch Hydrobiol Suppl* 115:29–44.